

Dark Radiation Confronting LHC in Z' Models

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Abstract

Recent cosmological data favour additional relativistic degrees of freedom beyond the three active neutrinos and photons, often referred to as “dark radiation”. Extensions of the SM involving TeV-scale Z' gauge bosons generically contain superweakly interacting light right-handed neutrinos which can constitute this dark radiation. In this letter we confront the requirement on the parameters of the E_6 Z' models to account for the present evidence of dark radiation with the already existing constraints from searches for new neutral gauge bosons at LHC7.

Additional heavy neutral Z' gauge bosons are predicted in many extensions of the standard model (SM) such as most Grand Unified Theories (GUT) and superstrings [1]. Generically a model with an extra $U(1)'$ gauge symmetry is characterized by the mass of the Z' , the $U(1)'$ gauge coupling and the chiral charges of the matter fields (in some cases including additional particles with exotic SM charges to cancel anomalies), and the possible mixing angle between the Z and Z' . Particularly well motivated and consistently anomaly-free constructions are Z' models based on the E_6 GUT group and for this reason they have been extensively studied in the literature. In what follows we will concentrate on these type of models though the results here presented can be easily generalized to other assignments of Z' charges and couplings.

Since E_6 is a rank 6 group, it contains in general two neutral gauge bosons beyond those of the SM. These couple to two new hypercharges ψ and χ corresponding to the $U(1)$ symmetries in $E_6/\text{SO}(10)$ and $\text{SO}(10)/\text{SU}(5)$ re-

	T_3	Y	$\sqrt{40}Y_\chi$	$\sqrt{24}Y_\psi$
$Q=L \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	$1/6$	-1	1
u_R	0	$2/3$	1	-1
d_R	0	$-1/3$	-3	-1
$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	$-1/2$	3	1
e_R	0	-1	1	-1
ν_R	0	0	5	-1

Table 1

The SM quantum numbers and hypercharges of the $U(1)_\chi$ and the $U(1)_\psi$ of the relevant fields.

spectively. These hypercharge quantum numbers for the SM fermions and right-handed neutrinos are given in Table 1. Here we focus on the case where the gauge sector contains only one additional $U(1)$ symmetry at low energies. Therefore there is a continuum of possible models where the new gauge boson couples to one linear combination of Y_χ and Y_ψ parametrized by a mixing angle β ¹.

$$Y_\beta = \cos \beta Y_\chi + \sin \beta Y_\psi, \quad (1)$$

In what follows will make our study for an arbitrary value of β which corresponds to the most general single Z' model where the new $U(1)$ can be embedded in a primordial E_6 symmetry. We can chose $0 \leq \beta \leq \pi$ since the charges merely change sign for $\beta \rightarrow \beta + \pi$. In this case the sign of the mixing angle between Z and Z' becomes physical. However the latest analysis of precision electroweak data [4] constraints the Z - Z' mixing angle to be at most $\mathcal{O}(10^{-3})$ for $M_{Z'} \lesssim 1$ TeV and theoretically the mixing angle is expected to decrease inversely proportional to $M_{Z'}^2$. For the sake of simplicity we will neglect the small effects associated with the Z - Z' mixing and set it to zero in our calculations. Finally the value of the $U(1)_\beta$ coupling is fixed by the condition of coupling constant unification $g_{Y_\beta} = \sqrt{\frac{5}{3}}g_2$ where g_2 is the $SU(2)$ coupling constant.

If present at the TeV scale these Z' bosons would lead to unmistakable signatures at colliders with the strongest constraints arising from searches of resonances decaying into dilepton final states at LHC7 [2, 3]. In Figure 1 we show the strongest present bounds on $\sigma(pp \rightarrow Z') \times \text{Br}(Z' \rightarrow l^+l^-)$ at 95% CL from these searches obtained with 5fb^{-1} luminosity [2] together with the theoretical expectations in the E_6 Z' models for different values of β . The theoretical expectations were obtained introducing the E_6 models in the pack-

¹ A special case that is often considered in the literature is $U(1)_\eta$, which in our convention corresponds to $\beta = \tan^{-1}(-\sqrt{5/3}) \simeq 0.71\pi$

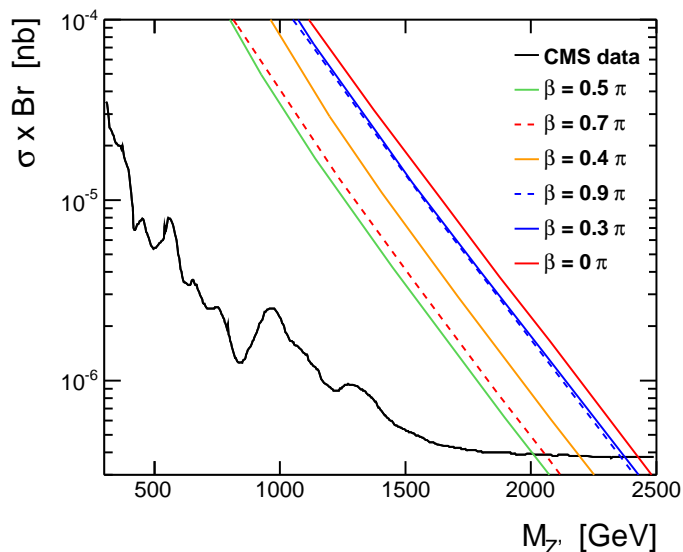


Fig. 1. 95% upper limits on the product ratio $\sigma(pp \rightarrow Z') \times \text{Br}(Z' \rightarrow l^+l^-)$ from the combined di-muon and di-electron searches in Ref. [2] as a function of the resonance mass. Also shown in the figure the predictions for E_6 Z' models for different values of the model parameter β as labeled in the figure. The curves corresponds from left to right to the values of β listed from top to bottom.

age MADEVENT [5] and with the CTEQ6L parton distribution functions [6]. They are in perfect agreement with the corresponding theoretical curves shown by the collaborations for some specific values of β . From the figure we read the most up-to-date bound on $M_{Z'}$ as a function of the model parameter β which we will use in the following and it is shown in Fig.4.

A TeV-scale Z' also has important cosmological implications. Since the right-handed neutrinos carry a non-zero $U(1)'$ charge, the $U(1)'$ gauge symmetry prevents the large right-handed Majorana masses needed for the ordinary neutrino seesaw mechanism. In this case right-handed neutrinos remain massless while the left-handed SM states must be light to account for the oscillation data [7]. Alternatively right-handed and left-handed neutrinos can combine to form three light Dirac neutrinos. Either way the lightness of the observed neutrino masses is generated by some additional mechanism and the three right-handed states are either light or massless and only couple to the SM sector via the Z' interactions. In this case the theory contains the right-handed neutrinos relativistic degrees of freedom in addition to photons and the three left-handed neutrinos of the SM which can contribute to the expansion rate of the Universe as a new form of "dark radiation" and consequently affect the cosmological observations.

In particular faster expansion would lead to an earlier freeze-out of the neutron to proton ratio and would lead to a higher ^4He abundance generated during

Big Bang Nucleosynthesis (BBN) [8]. At later times dark radiation would also alter the time for the matter-radiation equality with the corresponding impact in the observed cosmic microwave background (CMB) anisotropies as well as affect the large scale structure (LSS) distributions .

In Refs. [9, 10] it was first discussed in the context of BBN the implications of a superweakly interacting light particle, such as the right-handed neutrinos coupling to a heavy Z' . Because of their superweak interactions, such particles decouple earlier than ordinary neutrinos and consequently their contribution to the energy density budget of the Universe – and therefore to its expansion – is suppressed with respect to that of the left-handed neutrinos. The cosmic radiation content is usually expressed in terms of the effective number of thermally excited neutrino species, N_{eff} with its standard value being $N_{\text{eff}} = 3.046$. After their decoupling (for $T < T_{\text{dec}}^{\nu_L} < T_{\text{dec}}^{\nu_R}$) the three superweakly interacting light right-handed neutrinos contribute to ΔN_{eff} as:

$$\Delta N_{\text{eff}} = 3 \times \left(\frac{T_{\nu_R}}{T_{\nu_L}} \right)^4 = 3 \times \left(\frac{g(T_{\text{dec}}^{\nu_L})}{g(T_{\text{dec}}^{\nu_R})} \right)^{\frac{4}{3}} \quad (2)$$

where $g(T)$ is the effective number of degrees of freedom at temperature T . Neglecting finite mass corrections, $g(T) = g_B(T) + \frac{7}{8}g_F(T)$, where $g_{B,F}(T)$ are the number of bosonic and fermionic relativistic degrees of freedom in equilibrium at temperature T . Thus at $T_{\text{dec}}^{\nu_L} \sim 3$ MeV, $g(T_{\text{dec}}^{\nu_L}) = 43/4$ corresponding to three active neutrinos, e^\pm and photons. In calculating $g(T)$ at higher temperatures one must take into account the QCD phase transition at temperature T_c . Above T_c the quarks and the gluons are the relevant hadronic degrees of freedom, while below T_c they are replaced by the hadronic degrees of freedom. At present the estimated value of $T_c = 154 \pm 9$ MeV, [11] and the evolution of the energy and entropy across the QCD phase transition are obtained by means of state of the art lattice QCD simulations [12]. Using the results in Ref. [12] and including finite mass effects we obtain the T dependence of $g(T)$ (without the right-handed neutrino contribution) shown in the left panel in Fig. 2.

In the Z' models here discussed right-handed neutrinos are kept in equilibrium by their interactions with the SM fermions mediated by the Z' so

$$\begin{aligned} \Gamma_{\nu_R}(T) &= \sum_f \Gamma_f(T) = \sum_f \frac{g_{\nu_R}}{n_{\nu_R}} \langle v \sigma(\bar{\nu}_R \nu_R \rightarrow \bar{f} f) \rangle \\ &\equiv \sum_f \frac{g_{\nu_R}}{n_{\nu_R}} \int \frac{d^3 p}{(2\pi)^3} \frac{d^3 q}{(2\pi)^3} f_{\nu_R}(q) f_{\nu_R}(p) \sigma_f(s) v \\ &= \sum_f \frac{g_{\nu_R}}{8\pi^4 n_{\nu_R}} \int_0^\infty p^2 dp \int_0^\infty q^2 dq \int_{-1}^1 \frac{(1 - \cos \theta) \sigma_f(s)}{(e^{q/T} + 1)(e^{p/T} + 1)} d \cos \theta . \end{aligned} \quad (3)$$

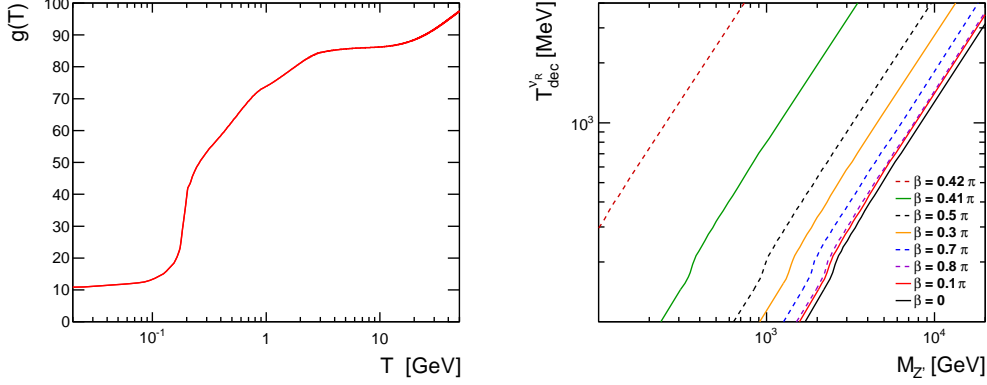


Fig. 2. Left: The effective number of degrees of freedom as a function of the temperature without including the contribution of the right-handed neutrinos. Right: Decoupling temperature of the right-handed neutrinos as a function of the Z' mass for different values of the model parameter β as labeled in the figure. The curves corresponds from left to right to the values of β listed from top to bottom.

$g_{\nu_R}=2$ and n_{ν_R} is the number density of a single generation of right-handed neutrinos which follows a Fermi-Dirac distribution $f_{\nu_R}(k) = \frac{1}{e^{k/T} + 1}$. $s = (p + q)^2 = 2pk(1 - \cos \theta)$ is the COM energy in the collision and $v = (1 - \cos \theta)$ where θ is the relative angle of the colliding right-handed neutrinos.

In Eq. (3) the annihilation cross section is

$$\begin{aligned} \sigma_f(s) &\equiv \sigma(\bar{\nu}_R \nu_R \rightarrow \bar{f} f) \\ &= N_C^f \frac{s \beta_f}{16\pi M_{Z'}^2} (Y_{\beta}^{\nu_R})^2 \left\{ \left(1 + \frac{\beta_i^2}{3}\right) \left[(Y_{\beta}^{f_L})^2 + (Y_{\beta}^{f_R})^2 \right] + 2(1 - \beta_i^2) Y_{\beta}^{f_L} Y_{\beta}^{f_R} \right\} \end{aligned} \quad (4)$$

where N_C^f is the number of colours of the fermion f and $\beta_f = \sqrt{1 - \frac{4m_f^2}{s}}$.

The ν_R 's will decouple when their interaction rate drops below the expansion rate of the Universe $H(T)$. Right before decoupling

$$H(T) = \sqrt{\frac{4\pi^3 G_N \left(g(T) + \frac{21}{4} \right)}{45}} T^2 \quad (5)$$

where we have included the $\frac{21}{4}$ contribution to the expansion due to the 3 generations of massless ν_R 's. The decoupling temperature is defined by the condition $\Gamma_{\nu_R}(T_{\text{dec}}^{\nu_R}) = H(T_{\text{dec}}^{\nu_R})$. Its value as a function of $M_{Z'}$ and β can be found by numerically solving this equality with the expressions in Eqs. (3) and (5) and $g(T)$ as given in Fig.2. We show it in the right panel of Fig.2. The coupling $Y_{\beta}^{\nu_R}$ vanishes for $\tan \beta = \sqrt{15}$, ie $\beta = 0.4196\pi$. Thus for this value of β the ν_R 's are never in equilibrium with the SM particles. Consequently,

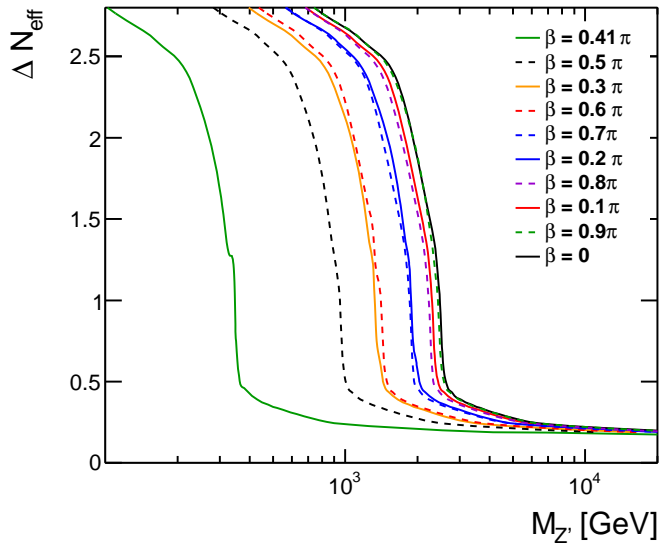


Fig. 3. The equivalent number of extra neutrinos ΔN_{eff} due to 3 generation of massless ν_R 's as a function of the Z' mass for several values of the model parameter β as labeled in the figure. The curves corresponds from left to right to the values of β listed from top to bottom.

as seen in the figure, $T_{\text{dec}}^{\nu_R} \rightarrow \infty$ independently of $M_{Z'}$ as $\beta \rightarrow \tan^{-1}(\sqrt{15})$. Conversely $Y_{\beta}^{\nu_R}$ is maximum for $\beta = 0, \pi$ ie for the $U(1)_{\chi}$ hypercharge so for a given $M_{Z'}$ $T_{\text{dec}}^{\nu_R}$ the lowest for this model.

Once we know $T_{\text{dec}}^{\nu_R}$ as a function of the model parameters we can derive the contribution of the right-handed neutrinos to the dark radiation at temperatures below their decoupling as Eq. (2). This is illustrated in Fig. 3 where we plot ΔN_{eff} as a function of the Z' mass for several values of the model parameter β . As expected as β approaches the decoupled model $\beta = \tan^{-1}(\sqrt{15}) \sim 0.42$, the additional number of effective neutrinos becomes small (asymptotically zero) for any value of $M_{Z'}$. We note that for the range of $M_{Z'}$ masses plotted in the figure, the minimum value of $\Delta N_{\text{eff}} \simeq 0.2$ corresponds to the plateau around $g(T_{\text{dec}}^{\nu_R}) \sim 86$ for the corresponding decoupling temperatures $3 \text{ GeV} \lesssim T_{\text{dec}}^{\nu_R} \lesssim 10 \text{ GeV}$ as can be seen in Fig. 2.

All this implies that the cosmological information on ΔN_{eff} can be used to constraint the Z' properties. In particular during most of the last two decades the measured primordial abundances of ^4He and other nuclei were used with this purpose [13–15]. Since at the time the observed abundances were compatible with the presence of no dark radiation, generically *lower* bounds on the Z' mass were derived.

This situation is altered at present as recent analysis of cosmological data suggest a trend towards the existence of “dark radiation” (see for exam-

ple [16–22]). The Wilkinson Microwave Anisotropy Probe (WMAP) collaboration found $N_{\text{eff}} = 4.34^{+0.86}_{-0.88}$ based on their 7-year data release and additional Large Scale Structure (LSS) data [16] at 1σ in a Λ CDM cosmology. In Ref. [17] $N_{\text{eff}} = 4.35^{+1.4}_{-0.54}$ was found in a global analysis including the data from cosmic microwave background (CMB) experiments (in particular the from WMAP-7), the Hubble constant H_0 measurement [23], the high-redshift Type-I supernovae [24] and the LSS results from the Sloan Digital Sky Survey (SDSS) data release 7 (DR7) halo power spectrum [25] in generalized cosmologies which depart from Λ CDM models by allowing not only the presence of dark radiation but also dark energy with equation of state with $\omega \neq -1$, neutrino masses, and non-vanishing curvature. More recent measurements of the CMB anisotropy on smaller scales by the Atacama Cosmology Telescope (ACT) [26] and South Pole Telescope [27] experiments seem to also favour a value of N_{eff} higher than predicted in SM. Cosmological constraints from BBN indicate, as well, that the relatively high ^4He abundance can be interpreted in terms of additional radiation during the BBN epoch [28–30] (see [31] for a recent review). In Ref. [31] using observed D and ^4He abundances and fitting simultaneously N_{eff} and the baryon asymmetry, it is found $N_{\text{eff}} = 3.71^{+0.47}_{-0.45}$ at 1σ .

This positive evidence of a non-zero ΔN_{eff} can be interpreted in the Z' models as evidence of a TeV scale Z' and used to quantitatively derive the required values of $M_{Z'}$ as a function of the model parameter β and to compare those with the present LHC7 constraints². We find that the 95%CL LHC7 lower bounds on $M_{Z'}$ as derived from Fig. 1 imply that within these scenarios the effective number of neutrinos is bounded to be³

$\Delta N_{\text{eff}}^{\text{max}}$	1.16	0.48	0.37	0.30	0.22	0	0.27	0.36	0.43	0.98	1.18
for $\frac{\beta}{\pi}$	0.00	0.10	0.20	0.30	0.40	0.419	0.50	0.60	0.70	0.80	0.90

(6)

We also show the results of this exercise in Fig.4 where we plot the values of $M_{Z'}$ required to generate two illustrative 1σ ranges of N_{eff} , $N_{\text{eff}} = 4.35^{+1.4}_{-0.54}$ ($0.76 \leq \Delta N_{\text{eff}} \leq 2.7$) as obtained in the analysis of Ref. [17] (right panel) and for the lower range presently favoured by BBN nucleosynthesis $N_{\text{eff}} = 3.71^{+0.47}_{-0.45}$ ($0.21 \leq \Delta N_{\text{eff}} \leq 1.13$) (left panel). Also shown in the figure are 95% CL the present bound from LHC7 as obtained from Fig. 1. As seen in the figure already with the existing bounds from LHC7 most of the values of $M'_{Z'}$ required to account for the larger amount of dark radiation ($N_{\text{eff}} = 4.35^{+1.4}_{-0.54}$) are disfavoured.

² Along these lines Ref. [32] presents an estimate of the corresponding gauge boson mass range for an specific model with two additional Z' bosons. See also Ref. [33].

³ In particular for the η model $\Delta N_{\text{eff}}^{\text{max}} = 0.42$.

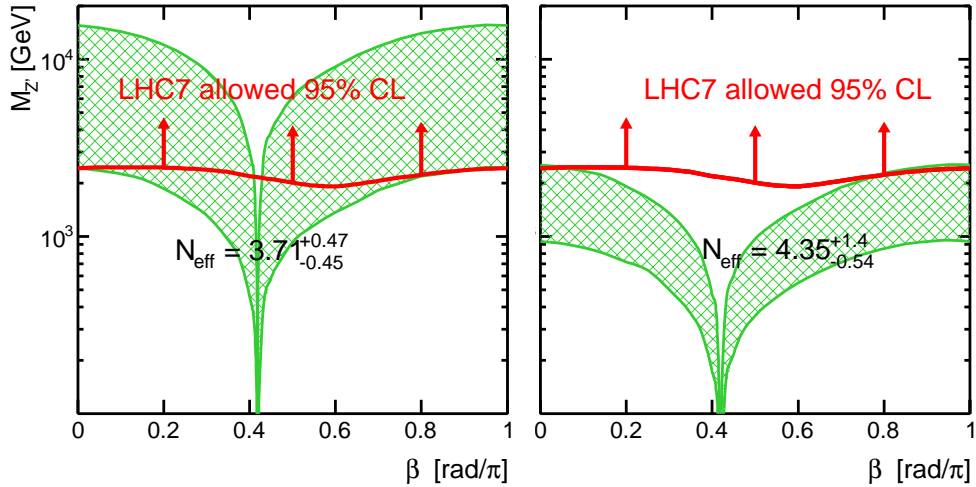


Fig. 4. Required values of $M_{Z'}$ for two illustrative 1σ ranges of N_{eff} , $N_{\text{eff}} = 4.35^{+1.4}_{-0.54}$ ($0.76 \leq \Delta N_{\text{eff}} \leq 2.7$) as obtained in the analysis of Ref. [17] (left panel) and for the lower range presently favoured by BBN nucleosynthesis $N_{\text{eff}} = 3.71^{+0.47}_{-0.45}$ ($0.21 \leq \Delta N_{\text{eff}} \leq 1.13$) (right panel). The solid red curve are the 95% CL lower bounds on $M_{Z'}$ from searches for Z' resonance in di-lepton production at LHC4 in Ref. [2].

In summary in this letter we have explored the possibility of accounting for the increasing evidence of dark radiation found in recent analysis of CMB, LSS, and BBN data in the framework of E_6 Z' models in the light of the present LHC7 constraints on these scenarios (which we display in Fig.1). In these models additional radiation exists in the form of three generations of relativistic right-handed neutrinos in an amount that depends on how long they are kept in equilibrium with the SM particles by the Z' interactions as we quantify in Figs. 2 and 3. We conclude that within the present 95% CL bounds already imposed by LHC7, these scenarios cannot account for extra radiation in excess of 1.25 effective neutrino species for any value of β and in excess of 0.5 effective neutrinos for models with $0.1 < \beta/\pi < 0.75$ (see Eq. (2)). The potential of the future LHC14 runs to further constraints the amount of dark radiation in these scenarios can be easily read from Fig.3. For example, should no resonance be found at LHC14, it is foreseeable that the lower bound 95% of $M_{Z'}$ will become at least ~ 5 TeV [34]. In this case the amount of dark radiation in these Z' models will be limited to at most that of 0.3 effective neutrinos.

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